

Chromium: a spin qubit with large spin to strain coupling

Quantum two level systems (“qubits”) strongly coupled to mechanical resonators can function as hybrid quantum systems with several potential applications in quantum information science. Access to a strong coupling regime, where non-classical states of a mechanical resonator are generated, could be achieved with solid state quantum bits whose energy levels have a large strain response. Thanks to their long coherence time, localized spins of individual magnetic atoms incorporated in a semiconductor host have great potential for storing quantum information in the solid state. The variety of magnetic transition elements that can be incorporated in semiconductors gives a large choice of electronic and nuclear spins as well as orbital momentum. Among these magnetic atoms, chromium is of particular interest, since strain can be used to control its magnetic anisotropy and thus influence its spin state.

Chromium (Cr) is incorporated in Group II-Group VI semiconducting compounds as Cr^{2+} ions carrying a localized electronic spin $S = 2$ and an orbital momentum $L = 2$. Moreover, most of the Cr isotopes have no nuclear spin which simplifies the spin level structure and its coherent dynamics. In the presence of bi-axial strain, the ground state of a Cr^{2+} ion is an orbital singlet with spin degeneracy $2S+1 = 5$. The chromium’s orbitals are sensitive to modification of the crystal field and thus connect its spin S to the local strain environment via the spin-orbit coupling.

For such a magnetic atom, static strain can be used to control its magnetic anisotropy and thus influence its spin memory. This large coupling of spin to strain, at least two orders of magnitude larger than for magnetic elements without orbital momentum, makes chromium a very promising spin qubit for the realization of hybrid spin-mechanical systems in which the motion of a microscopic mechanical oscillator would be coherently coupled to the spin state of a single atom.

To optically control the spin of an individual atom, we insert it in a quantum dot. In our experiments, the quantum dot is an island of the semiconducting compound Cadmium Telluride CdTe inside a layer of Zinc Telluride ZnTe. Absorption of an incident photon creates an electron-hole pair (an “exciton”) in the quantum dot (see Fig. 1). Inversely, a photon is emitted when the electron and hole annihilate each other. With a single Cr atom introduced in the dot, the energy and polarization of the photon emitted or absorbed by the dot depends on the spin state of the magnetic atom (Fig. 1). This is due to the exchange interaction present in the excited state, between the spin of the confined exciton and the spin (S_z) of the chromium.

In our work, we have demonstrated that the chromium spin can be used as an optically addressable qubit. First, the evolution of the quantum dot’s optical emission with magnetic field (see Fig. 1) revealed the large sensitivity of the Cr spin to local strain. Next, we used resonant optical excitation of the quantum dot to control and read out the Cr atom’s spin state. That is, we have shown that excitation with a laser beam tuned to the wavelength of one of these optical transitions can be used to initialize the state of the Cr spin and to probe its dynamics optically: The Cr atom behaves like an optically addressable, long-lived, spin-based memory.

Under optical excitation exactly resonant with an absorption transition, we can also enter the “strong coupling” regime where hybrid states of matter and light are created. The ground state of the magnetic atom is then “dressed” with light. The spin-dependent strong coupling with the laser field modifies the Cr atom’s energy levels. The optically controlled energy shift affects the spin dynamics of the atom and will be used for a coherent optical manipulation of the spin of an individual Cr atom.

Future applications of this new spin qubit in hybrid nano-mechanical systems will exploit the efficient mixing of the Cr spin states $S_z = +1$ and $S_z = -1$ induced by anisotropic, in-plane strain (see Fig. 1). The resulting mixed spin states, together with an exciton, form an optical “three level Λ (Lambda) system” (two ground states coupled optically with one excited state). This level structure opens the possibility of using coherent optical spectroscopy techniques for a sensitive probing of the local strain at the atom location and it makes Cr a very promising atomic scale strain-sensor.

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FURTHER READING...

“Individual Cr atom in a semiconductor quantum dot: Optical addressability and spin-strain coupling”

A. Lafuente-Sampietro, H. Utsumi, H. Boukari, S. Kuroda and L. Besombes

Phys. Rev. B **93**, 161301(R) (2016).

“Strain-induced coherent dynamics of coupled carriers and Mn spins in a quantum dot”

A. Lafuente-Sampietro, H. Boukari and L. Besombes

Phys. Rev. B **92**, 081305(R) (2015).

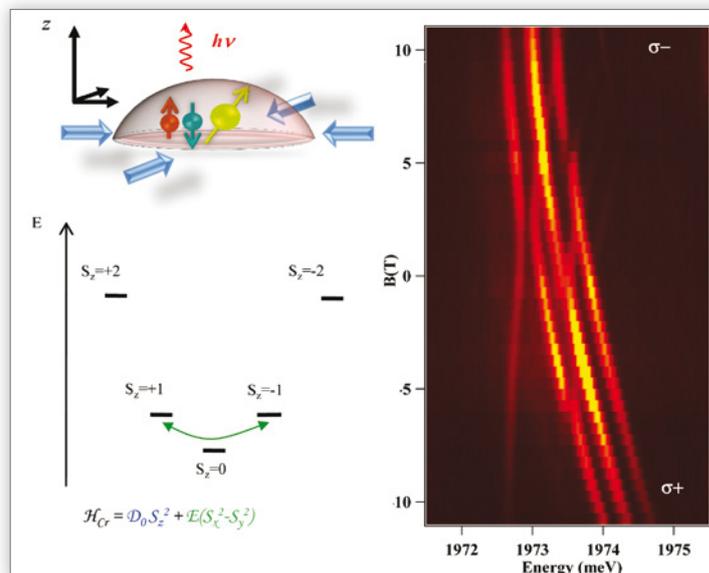


Fig. 1 - At top: A strained quantum dot containing a chromium atom (green) and an optically-created exciton (electron and hole, blue and red, with their spins).

At bottom: The energy levels of a Cr spin in the ground state of a quantum dot having large biaxial strain. The Cr fine structure is dominated by the magnetic anisotropy $D_0 S_z^2$. Anisotropic in-plane strain ($E(S_x^2 - S_y^2)$) couples its spin states $S_z = +1$ and $S_z = -1$.

At right: The dependence on magnetic field (B_z) of the photoluminescence spectrum (at low temperature, $T = 5$ K) for a CdTe/ZnTe quantum dot containing a single Cr atom. Only the Cr magnetic ground states $S_z = 0$ and $S_z = \pm 1$ are observed.